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Changes in Particle Pumping Due to Variation in Magnetic Balance Near Double-Null in DIII–D

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Abstract. We report on a recent experiment examining how changes in the divertor magnetic balance affect the rate that particles can be pumped at the divertor targets. We find that both the edge density of the core plasma and divertor recycling play important roles in properly interpreting this pumping result.

Previous studies on DIII-D have identified several important differences between double-null (DN) and single-null (SN) divertor operation. Small variations in the magnetic balance near-DN have large effects on both the power- and particle loadings at the divertor targets [1,2]. These most likely result from an interplay between the plasma geometry and ion particle drifts [3,4], e.g., "**B**×**∇**B" and "**E**×**B**" drifts [5,6]. Other studies have shown that changes in magnetic balance affect the core plasma [7] and where ELMs strike the vessel [8]. In this paper, we examine how variations in the magnetic balance impact the rate at which particles are removed from the core plasma via pumping.

Three examples of the poloidal cross-sections considered in this study are shown in Fig. 1: (a) unbalanced upper DN, (b) balanced DN, and (c) unbalanced lower DN. [For the sake of discussion, we refer to the shapes in Fig. 1(a,b,c) as "UDN", "BDN" and "LDN", respectively.] These plasmas exhibited type-1 ELMing [9] and high energy confinement, i.e., $\tau_E/\tau_{E89P} = (2.1–2.5)$, where τ_{E89P} is the 1989 L-mode energy confinement scaling [10]. Pumping was done from two poloidal locations. One pump was located inside the "dome" plenum and exhausted particles near the upper inner divertor target. The second pump was located under the "baffle" plenum and exhausted particles near the upper outer divertor target. The locations

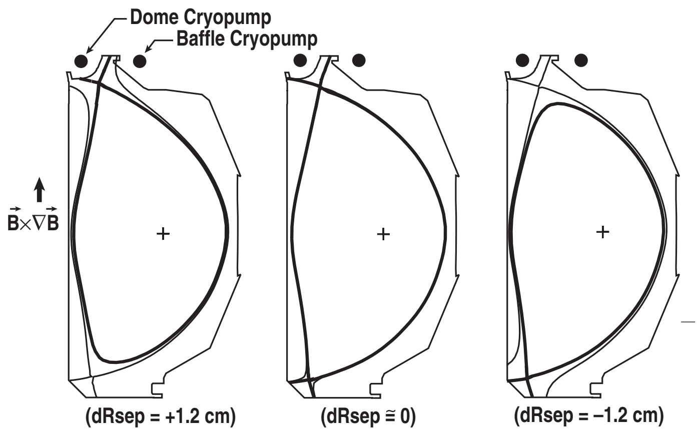

Fig. 1. The three basic equilibria used in this study: (a) DN biased toward the upper divertor (dRsep = +1.2 cm), (b) balanced DN (dRsep = 0), and (c) DN biased toward the lower divertor (dRsep = –1.2 cm). The "primary" (heavy) and "secondary" (light) divertor separatrices are shown. Characteristic parameters: I_P = 1.2 MA, B_T = 1.9 T, and P_{INJ} = 6–11 MW.

of the divertor legs were optimized to maximize the pumping rates. To quantify the divertor "magnetic balance," we define the quantity *dRsep* as $[R_L - R_U]$, where R_L is the radius of the lower divertor separatrix flux surface at the outer midplane and R_U is the radius of the upper divertor separatrix flux at the outer midplane.

The rates at which particles are exhausted by the dome pump (Γ_{DOME}) and by the baffle pump (Γ_{BAF}) depend differently on dRsep. Figure 2 shows that the ratio $\Gamma_{DOME}/\Gamma_{BAF}$ decreased steadily as the plasma shape changed from an UDN to a LDN. The *relative* importance of Γ_{BAF} to Γ_{DOME} almost doubled as dRsep = (+1 cm → 0 cm), and quadrupled as dRsep = (+1 cm → –1 cm).

A simple particle balance is useful to understanding these results: $0 = \Gamma_{INJ} - \Gamma_{DOME} - \Gamma_{BAF} - \Gamma_{WALL} - dN_C/dt$, where $[\Gamma_{INJ}]$ is the neutral beam fueling rate, $[dN_C/dt]$ is the time rate of change in the net number of particles entering/leaving the plasma system, and $[\Gamma_{WALL}]$ is the net number of particles into (+) or out of (-) the graphite tiles protecting the walls. With fixed pedestal density $n_{e,PED}$, Fig. 3 shows that Γ_{DOME} was more sensitive than Γ_{BAF} to small changes in dRsep near BDN. Moreover, the sum $[\Gamma_{DOME}+\Gamma_{BAF}]$ decreased by a third between UDN and BDN, implying a higher fraction of the particles had to be "pumped" by the graphite tiles to maintain constant $n_{e,PED}$. For dRsep ≈ +1.2 cm, $[\Gamma_{DOME}+\Gamma_{BAF}] \approx \Gamma_{INJ}$, and we surmise that constant $n_{e,PED}$ is maintainable with little or no wall pumping. For dRsep = 0, however, maintaining that <u>same</u> $n_{e,PED}$ is problematical, since this would require a <u>steady</u> Γ_{WALL} of ≈30-40% of Γ_{INJ}; wall pumping typically evolves over time.

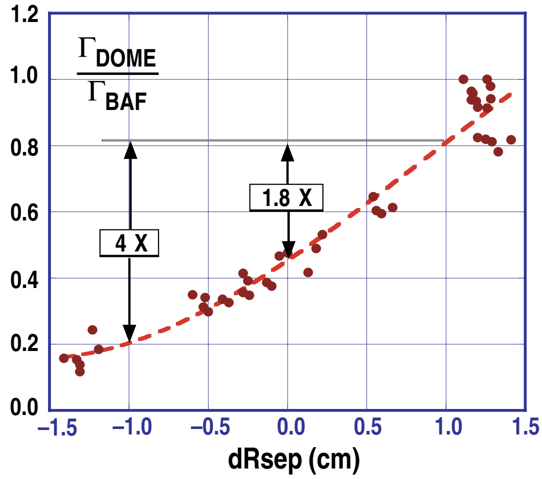

Fig. 2. The ratio $\Gamma_{DOME}/\Gamma_{BAF}$ depends on dRsep.

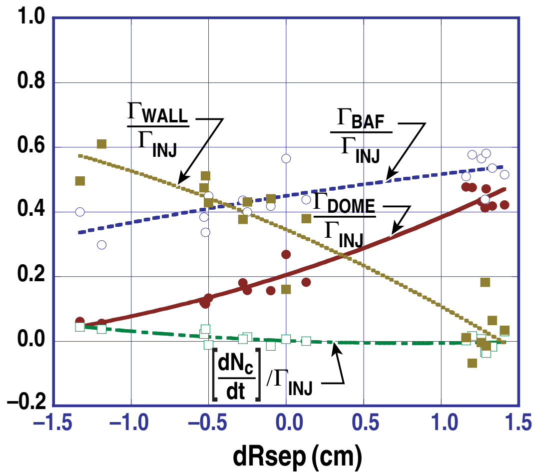

Fig. 3. Γ_{DOME} changed much more than Γ_{BAF} between dRsep = +1 to dRsep = –1 cm. The values of Γ_{INJ}, Γ_{DOME}, Γ_{BAF}, and dN_C/dt were determined by measurement, while Γ_{WALL} was deduced from a particle balance. Each term is normalized to Γ_{INJ}. Parameter window: $n_{e,PED}$ = (0.37–0.40) × 10^{20} m^{-3} and Γ_{INJ} = (9-13) torr l/s.

The sensitivity of Γ_{BAF} and Γ_{DOME} near BDN is understood in the following way. The number of particles that flow into the scrape-off layer (SOL) from the low-field side of the core plasma is much higher than the number of particles that flow into the SOL from the high-field side, this due mainly to the larger plasma surface area and steeper radial gradients in density on the low-field side [2]. About half of the particles that flow into the SOL on the low field side stream toward the upper outer divertor target, regardless of whether the shape is UDN or BDN. On the other hand, particles that flow into the SOL on the low field side have no direct route to upper inner divertor target in the BDN shape. Thus, changing the magnetic balance near the BDN should have a greater effect on Γ_{DOME} than on Γ_{BAF}.

Inherent to this discussion is that Γ_{DOME} than Γ_{BAF} are directly related to the number of particles striking the divertor targets. This is reasonable, if the neutrals at the divertor target can reach the pump entrance (and be subsequently pumped) without undergoing re-ionization, i.e., the mean free ionization pathlength of neutrals (λ) should be greater than the distance to the pump entrance. For the plasmas considered here, λ is several times the distance from the target to the entrance. Thus, some fraction of particles striking the divertor target will be directed into the plenum and be pumped, so that $(\Gamma_{DOME},\Gamma_{BAF}) \propto I_{SAT}$, where I_{SAT} is the number of particles striking the divertor target near the plenum entrance. This fraction is largely a function of divertor geometry and the ion particle flux profile closest to the plenum entrance [11].

Figure 4(a,b) shows a sizable dependence of Γ_{DOME} and Γ_{BAF} (normalized to Γ_{INJ}) on $n_{e,PED}$ for both UDN and BDN configurations. For $0 \leq$ dRsep$\leq +1.5$ cm, $(\Gamma_{DOME}, \Gamma_{BAF}) \propto [n_{e,PED}]^{(1.6\text{-}2.8)}$. (This strong dependence was the reason for tightly "windowing" on $n_{e,PED}$ in Fig. 3.) A simple "two-point" model [12] predicts a strong dependence, i.e., $\Gamma_{BAF} \propto I_{SAT} \propto [n_U]^2 \propto [n_{e,PED}]^2$. Here, n_U is the "upstream" density along the separatrix and is assumed here to be firmly tied to $n_{e,PED}$. Extrapolating the curves in Fig. 4(a,b) to the $n_{e,PED}$ for which the pumps would exhaust 100% of Γ_{INJ}, we find that $n_{e,PED} \approx 0.42$ and 0.5×10^{20} m^{-3} for the UDN and BDN cases, respectively.

Figure 5 shows that both Γ_{DOME} and Γ_{BAF} were nearly proportional to the recycling occurring next to their respective pump entrances, i.e., $\propto [\Phi_{REC}]^{(1.0\text{–}1.1)}$, where the recycling Φ_{REC} is characterized by the intensity of the D_α light radiating from in front of the dome and baffle entrances, respectively. We might expect this, since $[\Gamma_{DOME},\Gamma_{BAF}]$ and Φ_{REC} are both proportional to I_{SAT} in the lower density regime under consideration.

This linear relationship between $[\Gamma_{DOME},\Gamma_{BAF}]$ and Φ_{REC} suggests a useful connection between the poloidal distribution in recycling in *unpumped* discharges and $[\Gamma_{DOME},\Gamma_{BAF}]$ in *pumped* discharges. Recycling data from (similarly-prepared) *unpumped* discharges [7] are compared with the $\Gamma_{DOME}/\Gamma_{BAF}$ data from this study. The polynomial fit to the ratio

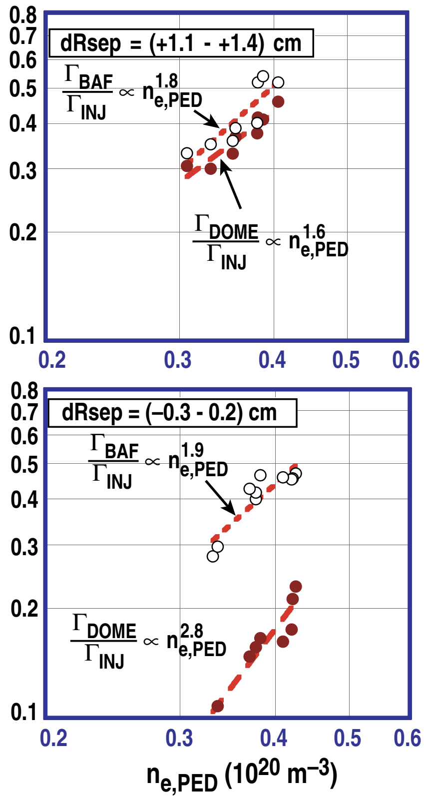

Fig. 4. $\Gamma_{BAP}/\Gamma_{INJ}$ (open circles) and $\Gamma_{DOME}/\Gamma_{INJ}$ (closed circles) depend strongly on the pedestal density for both (a) UDN: dRsep = (1.1–1.4) cm and (b) BDN: dRsep = (–0.3 – +0.2) cm.

$\Gamma_{DOME}/\Gamma_{BAF}$ (solid curve) is plotted versus dRsep in Fig. 6, along with the ratio $\Phi_{REC\text{-}IN}/\Phi_{REC\text{-}OUT}$ (closed circles), where $\Phi_{REC\text{-}IN}$ and $\Phi_{REC\text{-}OUT}$ are the intensities of the recycling light at the upper inner and upper outer divertor targets for the *unpumped* shots, respectively. Figure 6 shows a similar dependence in dRsep for $\Gamma_{DOME}/\Gamma_{BAF}$ and $\Phi_{REC\text{-}IN}/\Phi_{REC\text{-}OUT}$.

While active pumping on the two upper divertor legs may perturb the "natural" particle flows in the SOL and divertors and thus the pumping behavior, preliminary analysis suggests that the processes that may be pushing particles toward the divertor targets in *unpumped* cases are still present to some degree when pumping is occurring. We expect that, since the fraction of particles that are pumped at a target to be small compared with the incoming particle flux, the incident ion fluxes at that target would not be strongly affected by the pumping, at least for the low density, high energy confinement plasmas considered in this paper.

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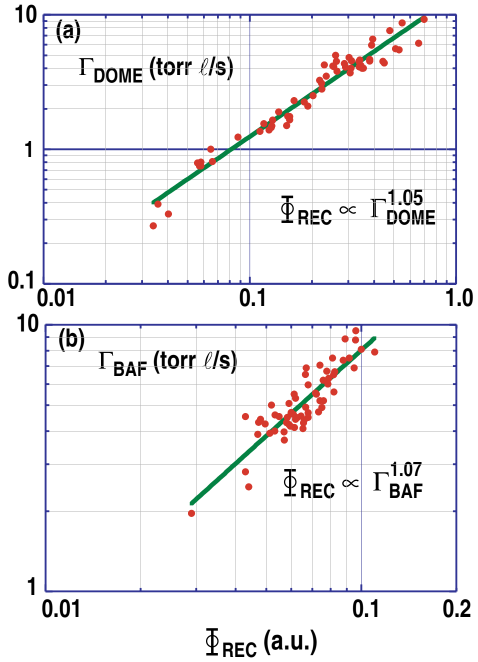

Fig. 5. (a) Γ_{DOME} and (b) Γ_{BAF} are plotted as a function of the recycling radiation [Φ_{REC}] adjacent to the opening of the dome and baffle pumps, respectively.

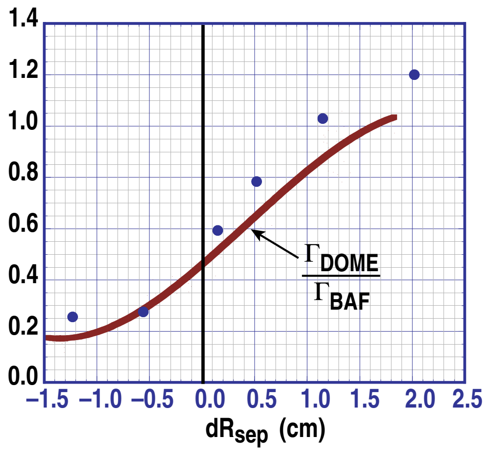

Fig. 6. A polynomial fit to the ratio $\Gamma_{DOME}/\Gamma_{BAF}$ (solid curve) is plotted vs dRsep for *pumped* plasmas. Superimposed is the ratio $\Phi_{REC\text{-}IN}/\Phi_{REC\text{-}OUT}$ (solid circles) for similar *unpumped* plasmas.

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